AD-A102 368   LEHIGH UNIV BETHLEHEM PA DEPT OF MECHANICAL ENGINEE--ETC F/G 20/4
              THEORETICAL & EXPERIMENTAL INVESTIGATION OF COHERENT STRUCTURE --ETC(U)
              JUN 81   D E ABBOTT, C R SMITH, J D WALKER   F49620-78-C-0071
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Annual Scientific Report

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THEORETICAL & EXPERIMENTAL INVESTIGATION OF COHERENT STRUCTURE

IN THE TURBULENT BOUNDARY LAYER

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by

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER **AFOSR-TR- 81-0605**	2. GOVT ACCESSION NO. **AD-A102368**	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* "THEORETICAL & EXPERIMENTAL INVESTIGATION OF COHERENT STRUCTURE IN THE TURBULENT BOUNDARY LAYER"		5. TYPE OF REPORT & PERIOD COVERED ANNUAL 1 May 80–30 May 81
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D E ABBOTT C R SMITH J D A WALKER		8. CONTRACT OR GRANT NUMBER(s) F49620-78-C-0071
9. PERFORMING ORGANIZATION NAME AND ADDRESS LEHIGH UNIVERSITY, BLDG. #19 BETHLEHEM, PA 18015		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2307/A2 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA BOLLING AFB, DC 20332		12. REPORT DATE 30 June 1981
		13. NUMBER OF PAGES 21
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*)		15. SECURITY CLASS. *(of this report)* UNCLASSIFIED
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

TURBULENT BOUNDARY LAYER
COHERENT STRUCTURE
FLOW VISUALIZATION
NUMERICAL MODELLING
VORTEX-WALL INTERACTIONS

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This project combines both experimental video flow visualization studies and theoretical investigations of a series of phenomenological and theoretical models based upon the three-dimensional details of convected, coherent structural elements of a turbulent flow as it interacts with a solid surface. The experimental program has considered a range of sub-problems including high Reynolds Number (4×10^6) turbulent flows, the effect of surface modification on low-speed streak formation, and the effect of vortex loop interaction with a

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solid boundary. To augment the visualization pictures, a computerized video-digitizing system has been implemented. Results show promise for obtaining quantitative data from flow visualization pictures. The specific thrust of the theoretical studies has been focussed on three areas: 1) how two- and three-dimensional vortex structures interact with wall boundary layers, 2) the development of a new type of prediction method for two-dimensional turbulent boundary-layer flows, and 3) improvement in numerical techniques for solving parabolic, boundary-layer equations.

RESEARCH OBJECTIVES

The basic objective of this research program is to obtain a clear physical and theoretical understanding of the dynamics of the turbulent boundary layer which will ultimately provide improved models for the turbulence quantities in the time-mean boundary-layer equations. The long range goals of the program continue to be both the improvement of the turbulent boundary-layer prediction methods and development of rational methods for control and/or modification of turbulent boundary layer behavior.

RESEARCH APPROACH

This project combines both experimental video flow visualization studies and theoretical investigations of a series of phenomenological and theoretical models based upon the three-dimensional details of convected, coherent structural elements of a turbulent flow as it interacts with a solid surface. The experimental program is considering a range of sub-problems including high Reynolds Number (4×10^6) turbulent flows, the effect of surface modification on low speed streak formation, and the effect of vortex loop interaction with a solid boundary. To augment visual studies, a computerized video-digitizing system has been implemented. Results show promise for obtaining quantitative data from flow visualization pictures. The specific thrust of the theoretical studies has been focussed on three areas: 1) how two- and three-dimensional vortex structures interact with wall boundary layers, 2) the development of a new type of prediction method for two-dimensional turbulent boundary-layer flows, and 3) improvement in numerical techniques for solving parabolic, boundary-layer equations.

SCIENTIFIC RESULTS

EXPERIMENTAL PROGRAM

The last 12 months have seen substantial use of the experimental facilities developed under the first two years of support. Work has progressed rapidly and, as will be described, significant understanding of turbulence structure and the processes which lead to turbulence have been developed. The past year has seen the completion of two theses, and the collection of material for five papers which are in preparation this summer. The following summarizes the results of the experimental program.

Utilizing the unique high-speed video flow visualization system developed under the present research funding, several significant advances have been made in understanding, characterizing, and controlling the wall region structure of turbulent boundary layers. Basic studies of wall-layer, low-speed streak structure have shown the structure to scale at a constant non-dimensional spanwise spacing of $\lambda^+ \cong 100$ for plate Reynolds numbers up to 4×10^6. Systematic visual examination of the streak behavior using simultaneous plan-side views have revealed that

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small loop vortices, generated during the energetic "bursting" (break-down) of the low speed streaks, are the mechanism which results in the regeneration of the streak structure. Detailed plan-end view studies (utilizing a fiber optic lens) have allowed the axially oriented legs of the loop vortices to be identified and their characteristics to be established. Initial results indicate that the wall-region loops may form the larger, previously observed outer-region structures by a com-plicated process of vortex coalescence. In addition, the use of longi-tudinally oriented surface ridges has been shown to successfully sta-bilize, and to some extent, modify the spanwise spacing of the low-speed streaks. This latter discovery is being explored further since streak control and modification are felt to be instrumental in the modification of drag and other surface transport processes.

In order to better understand the role that existing vortices in close proximity to a boundary may play in the turbulence generation pro-cess, basic studies of vortex-wall interactions have been conducted both in a quiescent environment and in a developing boundary layer. The basic interaction process has been shown to be an extremely com-plex, but organized, viscous-inviscid process which results in secondary and tertiary vortex loops of opposite rotation forming due to viscous action and wrapping around the primary vortex. A strong azimuthal stretching of these spawned vortices, which develops during the wrapping process, causes the initial vorticity of the primary vortex to be rapidly dispersed. It is felt that this complex, organized dispersion process has relevance not only to turbulence interactions near a boun-dary, but has ramifications with regard to other dispersive vortex-surface interactions, such as tip vortex-runway interactions. Note that excellent comparisons have been obtained between the experimental results and the analytical predictions of vortex-boundary layer inter-actions performed under the analysis portion of the present research effort.

A further development in the visualization system has been the final implementation of video-digitizing system which allows individual video pictures to be digitized and quantitatively analyzed on a mini-computer system. Excellent reproduction of digitized pictures is attainable; algorithms for establishment of velocity field data from digitized hydrogen bubble-wire pictures (Figure 1) are being completed.

ANALYTICAL PROGRAM

The analytical program is directed in four separate but related areas. The first of these areas is the development of improved tur-bulence models for prediction of the mean flow quantities. Models for the effects of pressure gradients and heat transfer in a low Mach number boundary layer have been developed. Currently a boundary layer model for mainstream turbulence typical of the gas turbine environment is in the latter stages of development. It is expected that an AFOSR technical report describing the progress on this part of the program will be completed by September 1981 following the MSME thesis of Mr. L.J. Yuhas; this thesis is currently in preparation and is projected

-2-
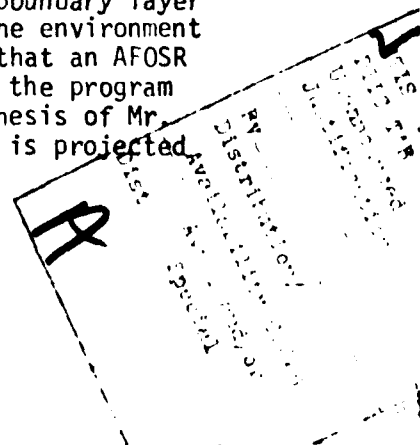
to be complete in August 1981. In figure 2, some typical results from these studies are illustrated. The data in this figure is relatively recent data taken at United Technologies Research Center in East Hartford and is mean profile data in a constant pressure turbulent boundary layer with mainstream turbulence. The data stations in figure 2 are labelled 1001 through 1006 and represent increasing levels of mainstream turbulence ranging from 0.02% to 4.7% respectively. The solid line represents a model profile containing a single parameter which was optimized to obtain a "best fit" to the data. It may be observed that the model profile represents the measured data very well; the results of this optimization were then used to correlate and subsequently incorporate the effects of mainstream turbulence in a simple eddy viscosity type model for use in a prediction method.

The second area is the development of improved numerical methods for parabolic partial differential equations and is an outgrowth of the need to improve the efficiency of boundary layer prediction methods. During the past year, two new methods have been developed which are more accurate than existing methods.

In figure 3, some typical results are illustrated from the MSME thesis work of Mr. W.C. Lee. In this figure, the performance of the two new methods is compared with that of two popular existing methods (the Crank-Nicolson method and the Keller Box method) for the solution of parabolic equations. The test case used in this comparison is the Howarth laminar boundary-layer problem which is for a diffuser-type boundary layer flow originating at $\xi=0$ and terminating with a predicted separation at $\xi \approx 0.9$. To provide a basis of comparison, the problem was solved with very small mesh sizes to provide an accurate "exact" solution; each method was then applied to the problem and a root-mean-square error computed at each ξ station. This error for all four methods is plotted in figure 3. Note the logarithmic scale for the RMS error and that the new methods out-perform the existing techniques in some ranges by an order of magnitude. The MSME thesis of Mr. W.C. Lee was recently completed in June 1981 and an AFOSR technical report is currently in preparation.

The third area currently under investigation is the asymptotic structure and turbulence models appropriate near the trailing edge of a turbine blade; here small zones of separation occur which lead to an interaction with the potential flow around the blade. Asymptotic methods are being used to investigate the multi-layer structure of the flow in the limit of high Reynolds numbers near such regions and to determine the effects on the flow about the entire blade.

Over the past two and a half years at Lehigh, the major effort in the analytical program has been focussed on the problem of vortex-wall boundary layer interactions. This study was initially motivated by the need to explain the origin of the bursting phenomenon in turbulent boundary layers and by preliminary experiments which suggested that convected vorticular structures in the outer layer had something to do with the bursting of the wall layer fluid. This portion of the program is closely associated with the experimental work and at this

stage the studies are of a rather *fundamental nature*; the objective
is to understand how vortex motion above a wall affects the viscous
boundary layer near the wall and to this end a number of analytical
and experimental studies have been carried out. In all cases studied
thus far, it emerges that the motion of the vortex induces an unusual
boundary layer separation leading to a rapid and violent ejection of
boundary layer fluid away from the wall; this inviscid-viscous inter-
action between the boundary layer and the inviscid flow away from the
wall, results in most cases in the creation of a secondary vortex and
thus provides a plausible physical explanation as to how turbulent
boundary layers are able to regenerate themselves with new vorticity
from the wall region. A complete description of the analytical work
on this problem may be found in the Ph.D. thesis of Dr. T.L. Doligalski[+]
which will *shortly appear* as an AFOSR technical report.

To illustrate a few representative results, some examples will
be summarized here. Consider first the boundary-layer flow patterns
illustrated in figure 4(a); these flow patterns are due to a vortex
which is in motion above the wall at $\eta=0$ and is being convected by a
shear flow similar to that in the outer regions of a turbulent boun-
dary layer. In this picture a mathematical transformation has been
used to transform the entire streamwise distance from upstream to down-
stream infinity to a finite range from 0 to 2; the parent vortex is
above the wall at $\xi=1$ and the picture is that seen by an observer
moving with the vortex. Note the unusual boundary layer separation
(that has occurred) gives rise to an uplifting of the streamlines in
the region behind the vortex. The situation is illustrated a short
time later in figure 4(b) where the *separation has* caused a severe
distention of the streamlines; at this stage a boundary layer eruption
and ejection of the induced secondary eddy is imminent.

A similar *phenomenon has* been studied in three dimensions by con-
sideration of a vortex ring in motion toward a plane wall. In figure
5 the temporal development of boundary layer flow is illustrated as
the ring approaches the plate; the flow is axisymmetric and consequently
only the flow in a cross section is illustrated. The center of the
ring is at $\xi=0$ and a transformation is used to compress the entire
streamwise extent of the flow field to a finite range; here $\xi=1$ cor-
responds to upstream infinity. The vortex ring position is above the
boundary layer and approximately at $\tau=0.25$ in the first picture; through
the second and third pictures the vortex ring stretches and moves out-
ward as it approaches the wall. The unsteady separation and *creation*
of a secondary vortex near the wall should be noted. The phenomenon
investigated here happens very rapidly as illustrated in figure 6
where the temporal development of the displacement thickness is illus-
trated; note the rapidly thickening boundary layer in the vicinity

of separation. It is evident from the theoretical calculations that the boundary layer will erupt and that a secondary ring vortex will be ejected from the wall region; this sequence of events has been confirmed and demonstrated in detail in the experimental portion of the program.

Based upon the fundamental studies carried out over the past two years, a production mechanism for turbulent boundary layer flows has been proposed. The sequence of events is depicted schematically in figure 7. In figure 7(a) a convected parent vortex influences the boundary layer near the wall and a thickening of the boundary layer occurs in the region behind the moving vortex. The rate of this thickening depends on the parent vortex strength and also on its distance from the wall. The upwelling fluid from the boundary layer enters the inviscid region in figures 7(b) to 7(c) to an increasing extent and as it does so it penetrates a region of cross-flow in the inviscid region. This cross flow acts to overturn the thickening boundary layer and a new vortex is created in a strong viscous-inviscid interaction between the inviscid flow and the boundary layer flow. Finally in figure 7(f), the spawned vortex (marked S) and the parent are convected downstream and ultimately both may be expected to interact again with the boundary layer.
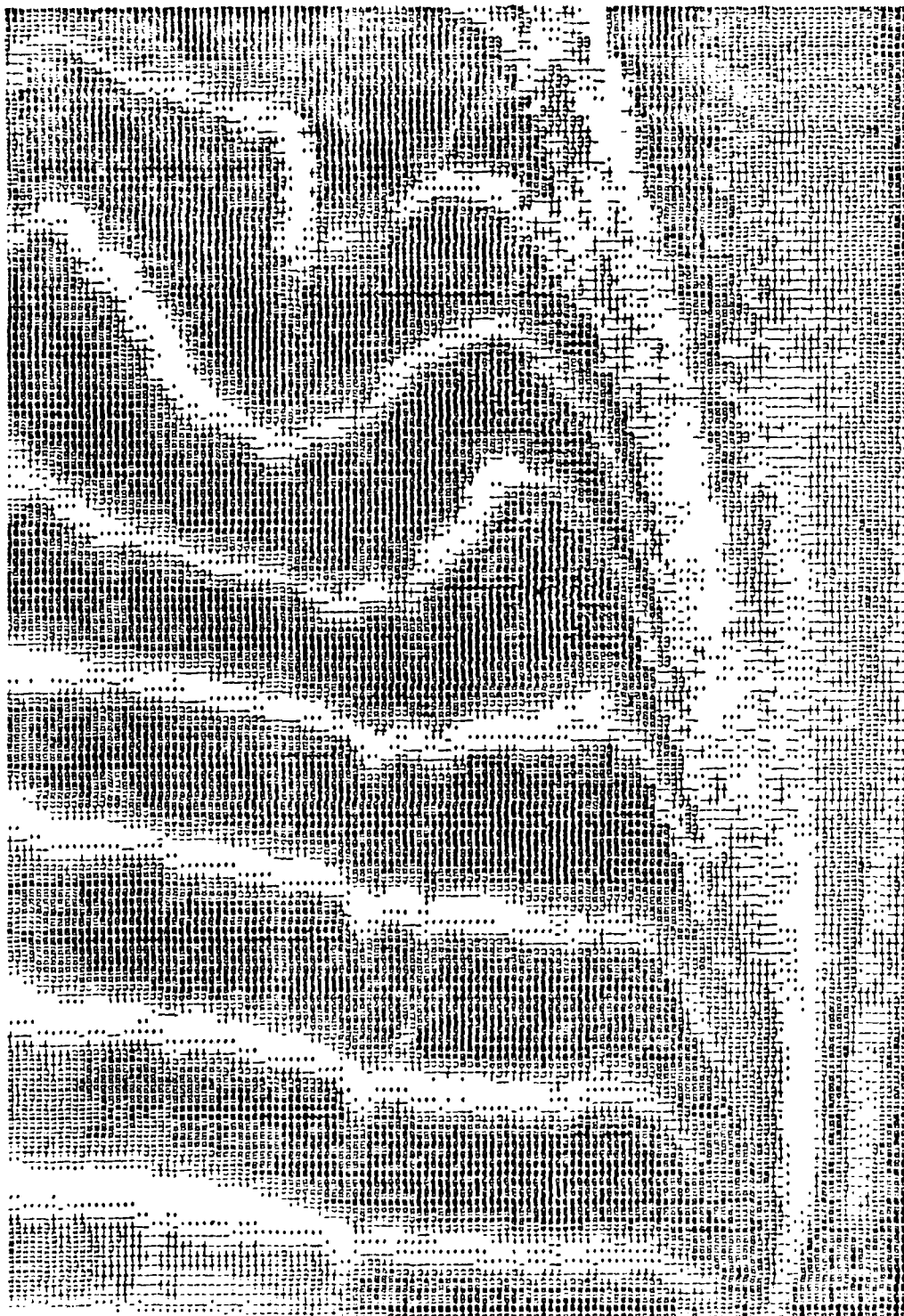
Figure 1 . HYDROGEN BUBBLE LINES IN A TURBULENT BOUNDARY LAYER

AFOSR Flow Visualization Research
Prof. C.R. Smith
Dept. of Mechanical Engineering and Mechanics
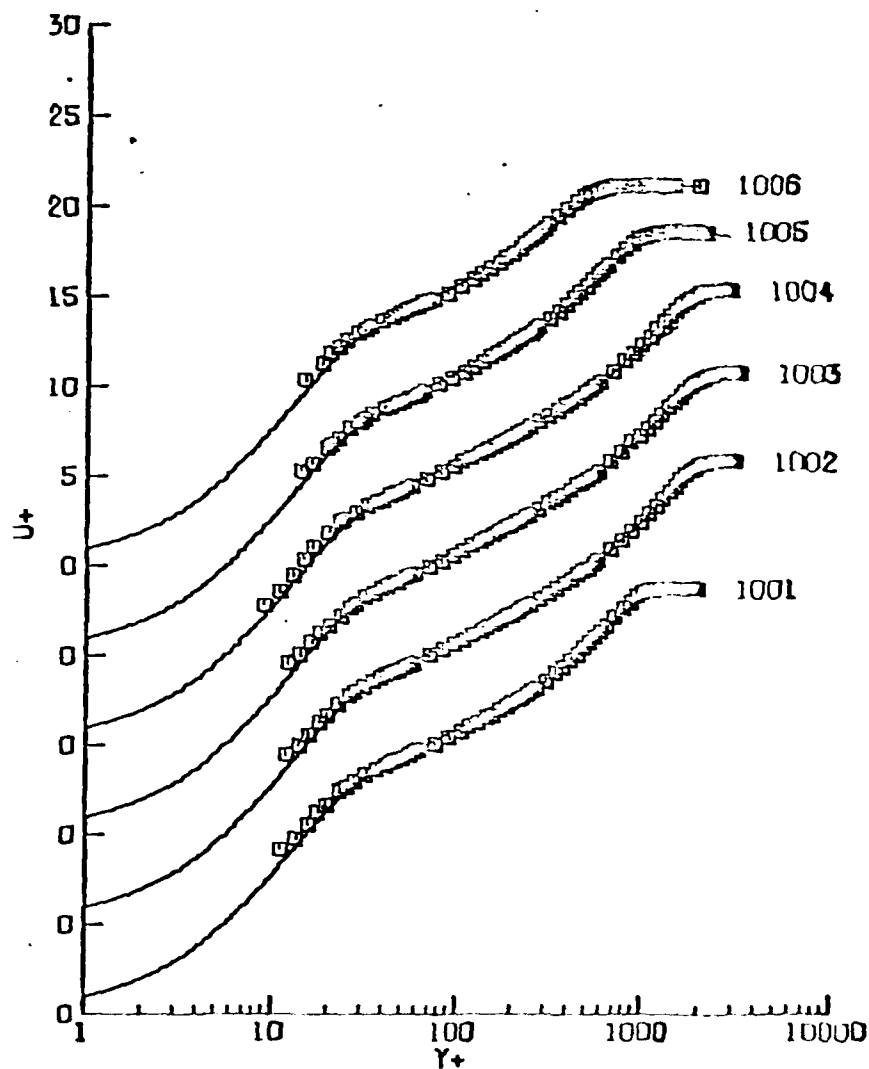Lehigh University

Figure 2. Turbulence model development; representation of mean
velocity profile data in a turbulent boundary layer
with mainstream turbulence. The squares are measured
data and the solid line is the model profile; successive
data stations are for increasing levels of mainstream
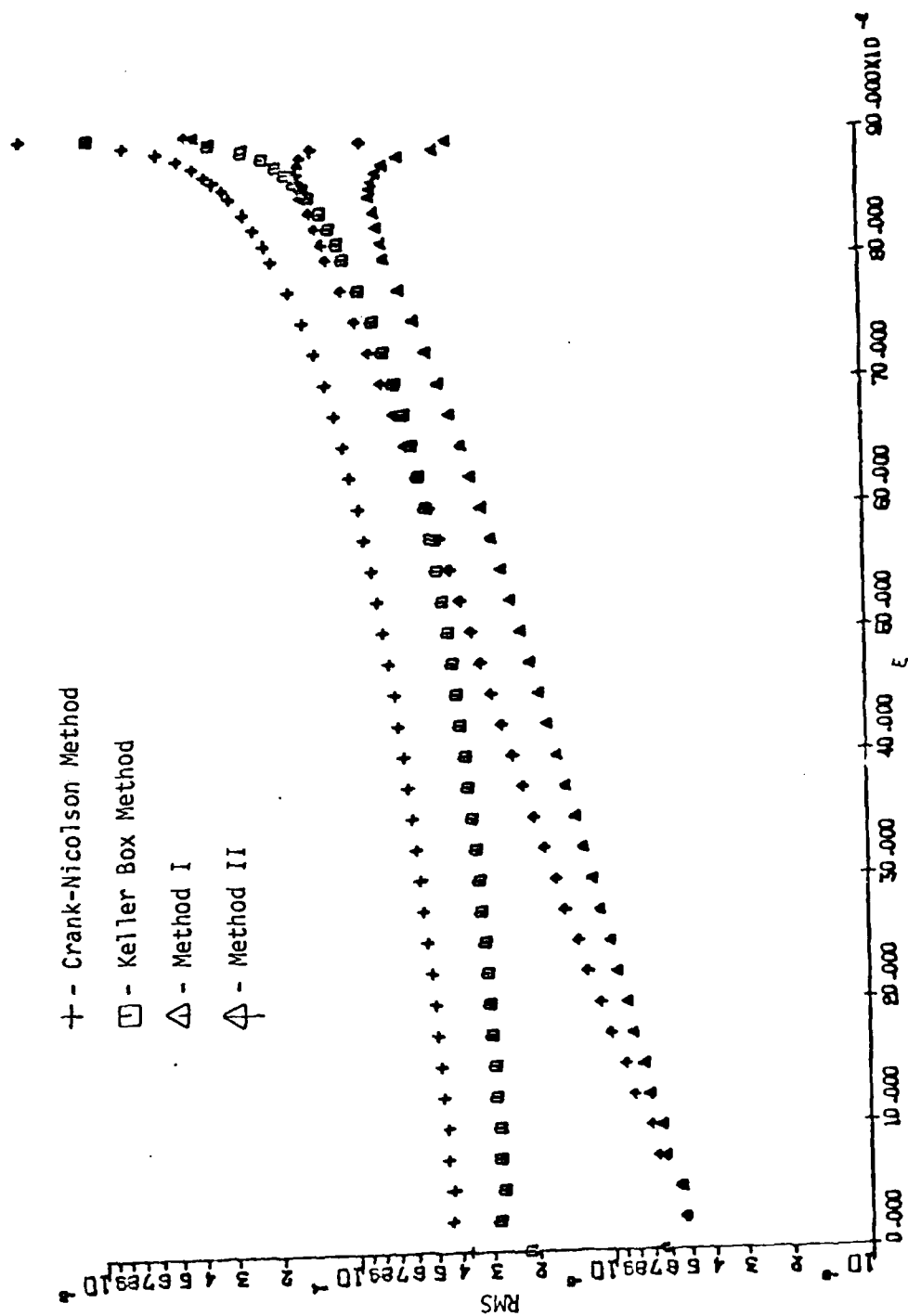turbulence.

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Figure 3. Comparison of RMS error for the Howarth flow problem.

+ - Crank-Nicolson Method
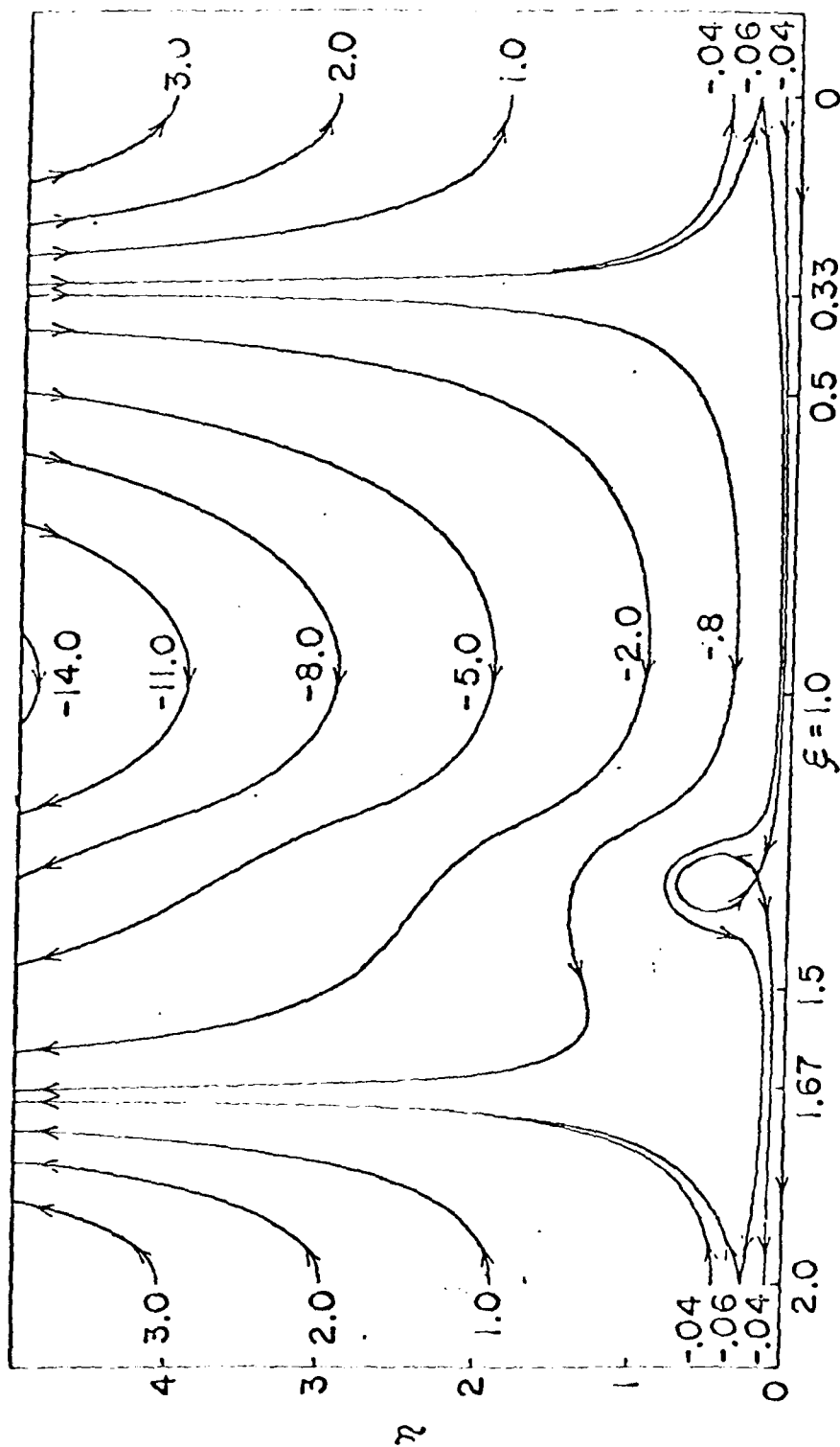
□ - Keller Box Method

△ - Method I

◁ - Method II

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Figure 4(a): Boundary layer streamline patterns for a vortex convected in a shear flow; reference frame is convecting with vortex. Arrows denote direction of flow.
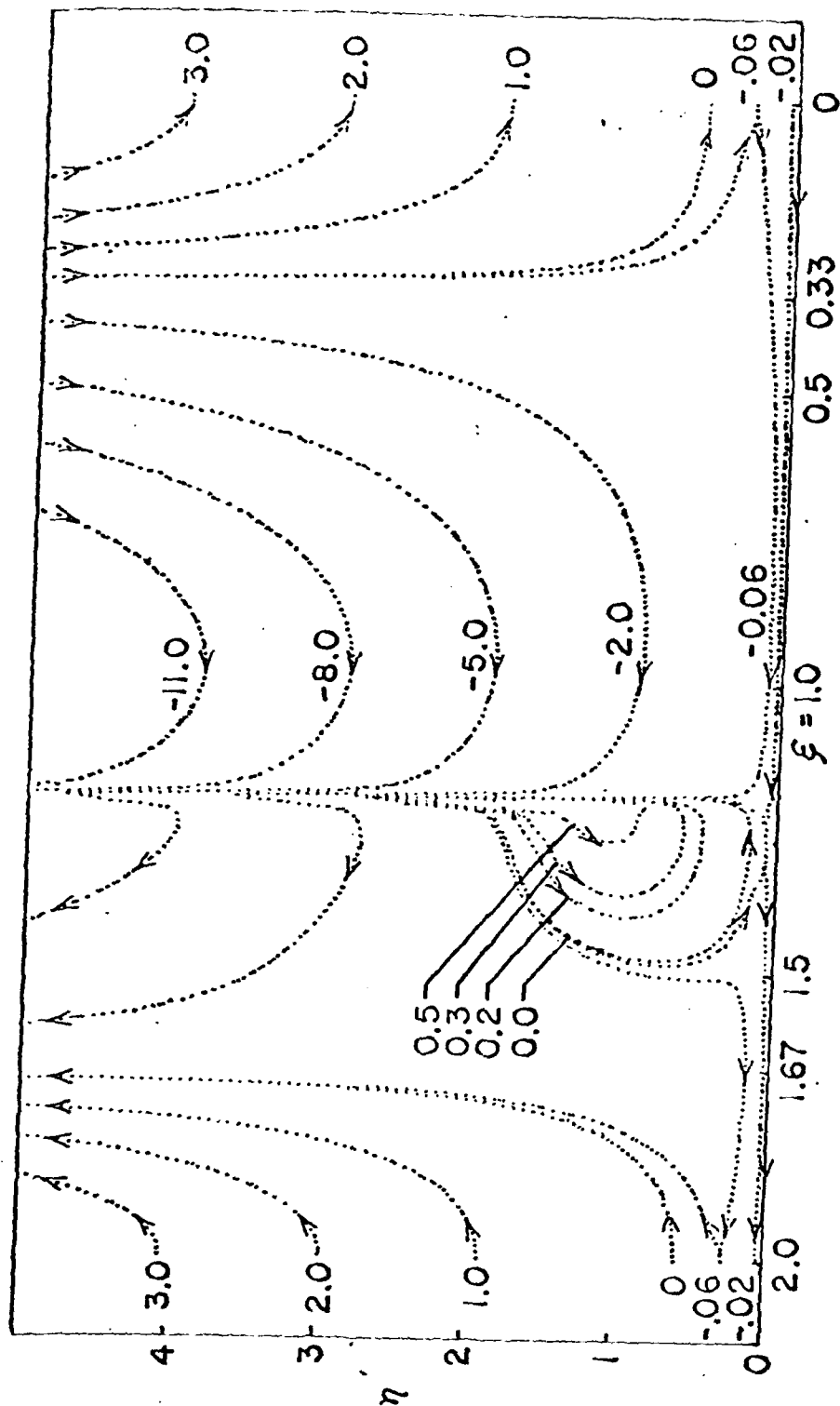
Figure 4 (b): Same case as in Figure 4 (a) a short time later.

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Figure 5: Temporal development of boundary layer flow due to
a vortex ring approaching the wall. The flow is
axisymmetric and streamline patterns are for a
cross section. The center of the ring is at $\zeta = 0$.

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Figure 6: Temporal development of the displacement thickness
for the boundary layer due to an impinging ring
vortex.

Figure 7: Proposed mechanism for turbulent boundary layer production.

PREVIOUS ACCOMPLISHMENTS

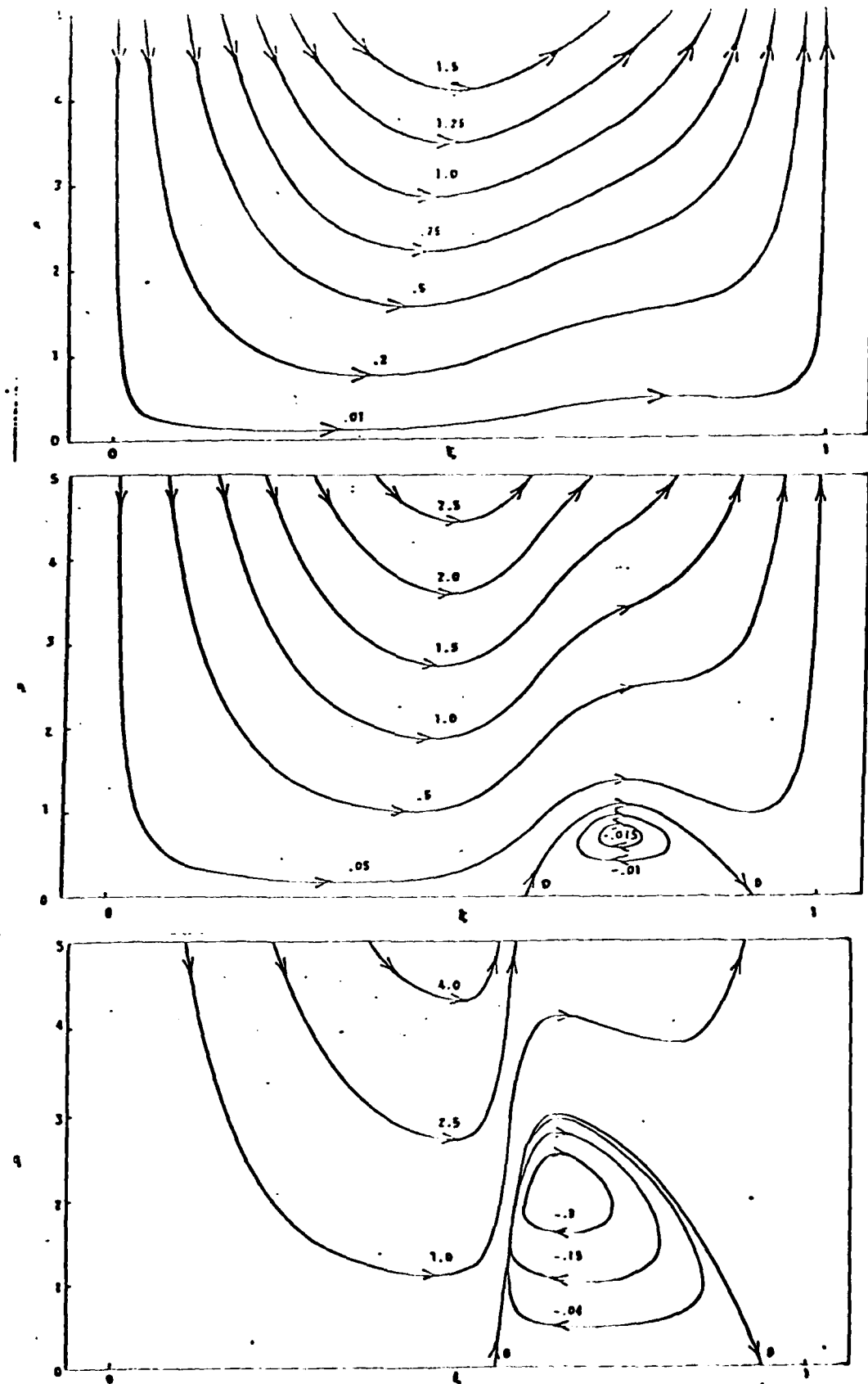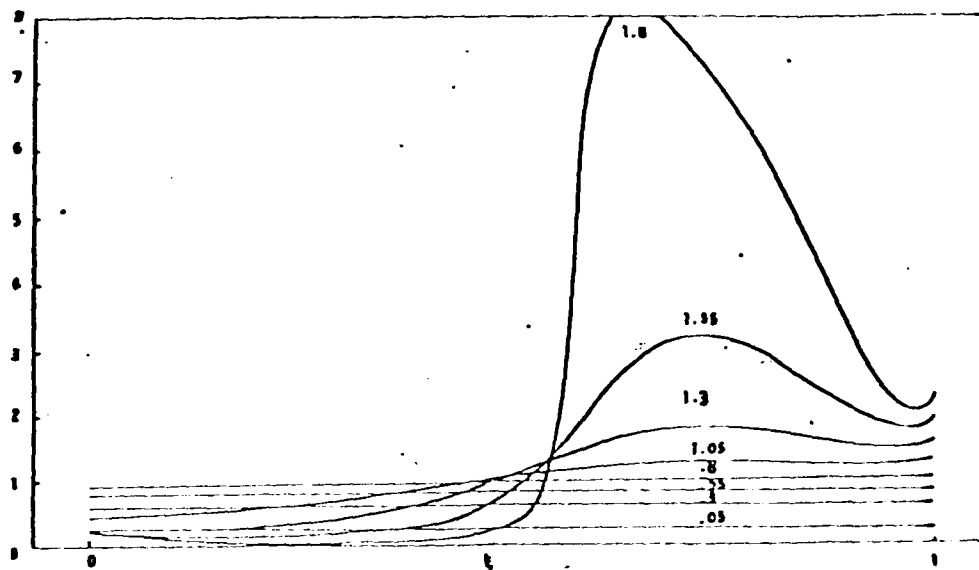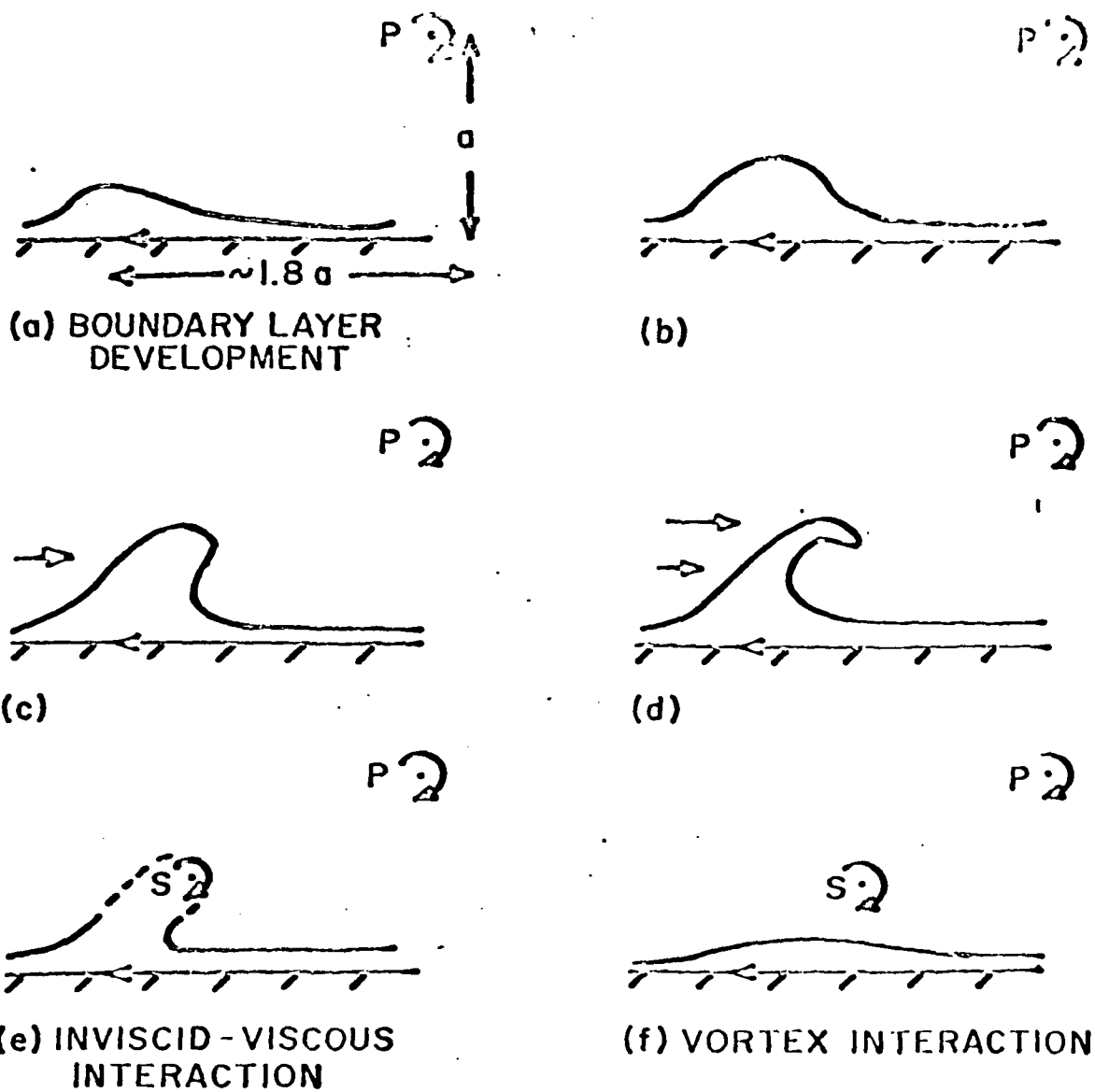### EXPERIMENTAL PROGRAM

a) Was first experimental facility to employ video recording-playback and moving reference frame observation of turbulent structure.

b) Demonstrated the ability of a convected vortex structure to promote a burst-like behavior.

c) Experimentally demonstrated the interaction of an impinging vortex on a viscous boundary layer.

d) Visually confirmed the existence of strong axial vortices in a turbulent boundary layer, and quantitatively documented the frequency of occurrence and vortex strengths.

e) Illustrated the effect of Reynolds number and surface modification on low speed streak spacing; showed streaks to be self-perpetuating and controllable by passive means.

ANALYTICAL PROGRAM

a) Developed a unique unsteady wall layer model for describing the mean profile in a turbulent boundary layer.

b) Developed both 1) a fast and accurate turbulent boundary layer prediction method and 2) the simplified turbulence models required for a).

c) Was the first analytical effort to elucidate the effects of vortex motion on boundary layers, which has particular implications with regard to aircraft trailing vortices and turbulent boundary layers.

d) Proposed a plausible physical mechanism for the regeneration of turbulence in a boundary layer.

e) Development of improved numerical methods for parabolic equations.

TECHNOLOGICAL SIGNIFICANCE

The principle objectives of the present research program are
(a) to develop an understanding of the fundamental mechanisms of tur-
bulent boundary layer flows through a combined theoretical and experi-
mental investigation and (b) from this understanding to develop improved
techniques for the prediction of the time-mean behavior of such flows.
The present program has successfully identified the effect that vor-
tex motion induces in viscous boundary layers; previously this effect
was largely unknown, and is that a boundary layer will ultimately erupt
in response to vortex motion above it. Such information is important
in the development of mechanical means for drag reduction and boundary
layer control. Also under the current program, a prediction method
is being developed which is consistent with the observed structure of
the turbulent boundary layer. The unsteady wall layer model developed
under this program is currently being used at Detroit Diesel Allison,
Division of GMC in an Air Force sponsored program; here a prediction
method for end wall boundary layers in compressors is being developed
with the objective of predicting blockage effects due to the boundary
layers on the hub and shroud of a compressor. A method of data reduc-
tion (using the unsteady wall layer model) is currently being used in
an experimental program at United Technologies Research Center in evalua-
ting and representing velocity and temperature profile data. Tur-
bulence models for the transport of heat and momentum in the outer
region of a turbulent boundary layer are also under development in the
current program and it is planned to use these models in the near
future in a new UTRC prediction program. A primary objective here
is to develop the capability to predict skin friction and heat trans-
fer effects on gas turbine blades. The development of models and
techniques to calculate trailing edge flow separation on turbine
blades is in progress under the current program in collaboration with
UTRC.

The development of the improved numerical methods for parabolic
equations over the past year is significant in the development of
faster and more accurate numerical methods for the boundary layer
equations; in addition, parabolic equations occur in many other phy-
sical applications, such as heat and mass transfer, and consequently
such techniques are valuable in general application.

Finally, the analytical procedure developed under this program
to correlate the effects of heat transfer, pressure gradient and main-
stream turbulence and incorporate these effects into a simple tur-
bulence model is believed to have potential application for other
turbulence effects and turbulent boundary layer prediction.

The technological significance of the experimental effort can be condensed into two basic categories:

1) Modeling information on turbulence statistics and flow structure which is essential for development of improved prediction programs, and

2) Techniques for the rational control of turbulent boundary to effect reduced drag or to augment heat and mass transfer.

Our program has been successful in the first category by determining the effect of flow parameters on wall region scaling of low speed streak flow structures and the quantitative strength of the vortices which form the low speed regions. This information is of immediate use in certain prediction programs incorporating flow structure models. The techniques for rational control of wall region flow structure have already provided a mechanistic explanation for why certain longitudinal surface modifications can effect drag reduction. The qualitative results of the present work have been used to complement the quantitative drag reduction work by surface modification being carried on at NASA Langley. In addition, it appears that the flow structure changes due to the present surface modification technique may have a far reaching effect on flow separation. Preliminary results indicate the possibility of "structuring" a surface so as to locally increase turbulent mixing, resulting in reduced flow separation and thus reduced form drag.

ASSOCIATED PUBLICATIONS, PRESENTATIONS AND THESES

PUBLICATIONS

[1] Walker, J.D.A., "The Boundary Layer Due to Rectilinear Vortex"
     Proc. R. Soc. Lond. A., Vol. 359, 1978, pp. 167-188.

[2] Doligalski, T.L. and Walker, J.D.A., "Shear Layer Breakdown Due
     to Vortex Motion," Proceedings of the AFOSR Workshop on Coherent
     Structure of Turbulent Boundary Layers, C. Smith and D. Abbott, eds.,
     Lehigh University, November, 1978, pp. 288-339.

[3] Smith, C.R., Brown, J.J. and Crosen, D.A., "Hydrogen Bubble-Wire
     Simulation of a Transverse Vortex in a Turbulent Boundary Layer,"
     Technical Report CFMTR-78-2, School of Mechanical Engineering,
     Purdue University, April 1978.

[4] Smith, C.R., "Visualization of Turbulent Boundary-Layer Structure
     Using a Moving Hydrogen Bubble-Wire Probe," Proceedings of the
     Workshop on Coherent Structure of Turbulent Boundary Layers,
     Lehigh University, May, 1978.

[5] Smith, C.R. and Abbott, D.E., Proceedings of Workshop on Coherent
     Structure of Turbulent Boundary Layers, Lehigh University,
     November 1978.

[6] Walker, J.D.A., "Position Paper for Colloquium on Turbulent Flow
     Separation", SQUID Colloquium on Turbulent Flow Separation, January
     18-19, Southern Method. University, (to be published in SQUID
     report), 1979.

[7] Doligalski, T.L., Smith, C.R. and Walker, J.D.A., "A Production
     Mechanism for Turbulent Boundary Layer Flows", presented at the
     "Symposium on Viscous Drag Reduction", Progress in Astronautics
     and Aeronautics, Vol. 72, G.R. Hough, ed., 1980., pp. 47-71.

[8] Smith, C.R., Schwartz, S.P. Metzler, S.P., and Cerra, A.W.,
     "Video Flow Visualization of Turbulent Boundary Layer Streak
     Structure," in Flow Visualization II, W. Merzkirch, ed.,
     Hemisphere Pub. Co., Washington, D.C., 1981.

PRESENTATIONS

J.D.A. WALKER

1. "Shear Layer Breakdown due to Vortex Motion", AFOSR Workshop on Coherent Structure of Turbulent Boundary Layers, Bethlehem, PA, May, 1978.

2. "Survey of Analytical and Experimental Investigation of the Coherent Structure of Turbulent Boundary Layers", invited seminar, United Technologies Research Center, East Hartford, Connecticut, June, 1978.

3. "The Effect of Vortex Motion on Wall Boundary Layers", First Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, Stanford, California, July 24, 1978.

4. "Some Aspects of Turbulent Boundary Layer Separation", SQUID Colloquium on Turbulent Flow Separation, Southern Methodist University, July 19, 1979.

5. "Boundary Layer Eruptions induced by Vortex Motion", Second Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, East Lansing, Michigan, July 29, 1979.

6. "A Production Mechanism for Turbulent Boundary Layer Flows", Symposium on Viscous Drag Reduction, Dallas, Texas, November 7, 1979.

7. "The Boundary Layer due to a Vortex Convected in a Shear Flow", 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November 18, 1979.

8. "Vortex Wall Interactions", invited seminar, The Ohio State University, Columbus, Ohio, May 30, 1980.

9. "Boundary Layer Due to an Impacting Vortex Ring", 33rd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Cornell U., Ithaca, N.Y., 23 November 1980.

C.R. SMITH

1. "Visualization of Turbulent Boundary-Layer Structure Using a Moving Hydrogen Bubble-Wire Probe," Workshop on Coherent Structure of Turbulent Boundary Layers, Bethlehem, Pennsylvania, May 1978.

2. "Visualization of Coherent Turbulence Structure Using Conventional Video Technique," First Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, Stanford, California, July 24, 1978.

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3. "High-Speed Video Analysis of Flow Visualized Turbulence Structure," Second Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, East Lansing, Michigan, July 28, 1979.

4. "The Visualization of Localized, Convected Fluid Pockets in the Wall Region of a Turbulent Boundary Layer," 31st Annual Meeting, Division of Fluid Dynamics, American Physical Society, Los Angeles, California, November, 1978.

5. "Visualization of Turbulent Boundary-Layer Structure Using a Moving Hydrogen Bubble-Wire Probe and a T.V. Viewing System," invited seminar, Penn State Department of Mechanical Engineering, May 3, 1979.

6. "A Production Mechanism for Turbulent Boundary Layer Flows," Symposium on Viscous Drag Reduction, Dallas, Texas, November 7, 1979.

7. "Streak Formation in Turbulent Boundary Layers: Recent Observations," 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November 1979.

8. "Experimental Observation of Vortex Loop-Boundary Layer Interactions," 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November 1979.

9. "Video Flow Visualization of Coherent Structures in a Turbulent Boundary Layer", invited seminar, University of Maryland Fluid Mechanics Seminar Series, 7 March 1980.

10. "The Presence of Axial Vortices in Turbulent Boundary Layers: A Visual Study," invited talk, Ohio State University Colloquium on Turbulent Boundary Layer Structure, 21-23 March, 1980.

11. "Flow Visualization Results in the Near-Wall Region of a Turbulent Boundary Layer," Applied Mechanics Seminar, University of Southern California, Los Angeles, CA., July 17, 1980.

12. "Video Flow Visualization of Turbulent Boundary Layer Flows", International Symposium on Flow Fisualization, Bochum, W. Germany, September 11, 1980.

13. "Flow Visualization Using High Speed Video Techniques," Invited
&   seminars at Max-Planck Institute, Gottingen, W. Germany, September 15
14. 1980 and at University of Lercester, England, September 18, 1980.

15. "Effects of Reynolds Number and Surface Modifications on Streak Spacing in Turbulent Boundary Layers", 33 Annual Meeting, Division of Fluid Dynamics, APS, Ithaca, N.Y., 23 November 1980.

16. "Effects of Surface Modifications on Turbulent Boundary Layer Structure," Invited Seminar NASA Langley Research Center, Virginia, 18 December 1980.

D.E. ABBOTT

1. "Theoretical and Experimental Investigation of Turbulent Boundary-Layer Structure-An Integrated Research Program," Thermal-Science Colloquium, Rutgers University, October, 1978.

2. "Investigation of the Fundamental Structure of Turbulent Boundary Layers," Ingersoll-Rand Corp., Phillipsburg, N.J., December, 1978.

3. "Specialists Workshop on Coherent Structure in Turbulent Boundary Layers", panalist, East Lansing, Michigan, July, 1979.

4. "Review of the A.F.O.S.R.-Lehigh University Program on Turbulent Boundary Layers," Lehigh University Research Center's Review, September, 1979.

5. "Boundary Layers," Technical Session Chairman, 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November, 1979. (Also elected Fellow, American Physical Society.)

THESES COMPLETE

1. Scharnhorst , R.K., "An Analysis and Prediction of Nominally Steady, Two-Dimensional, Constant Property Turbulent Boundary Layer", Ph.D. thesis, Purdue University, Aug. 1978.

2. Doligalski , T.L., "The Influence of Vortex Motion on Wall Boundary Layers", Ph.D. Thesis, Lehigh University, October 1980.

3. Metzler, S.P., "Processes in the Wall Region of a Turbulent Boundary Layer", MSME thesis, Lehigh University, December 1980.

4. Schwartz, S.P., "The Detection and Quantification of Axial Vortices in the Wall-Region of a Turbulent Boundary Layer", MSME thesis, Lehigh University, June 1981.

5. W.C. Lee, "Two Improved Methods for Parabolic Equations", MSME thesis, Lehigh University, June 1981.

THESES IN PROGRESS (expected completion date in parentheses)

1. Yuhas, L.J., "Prediction of Mainstream Turbulence Effects on Turbulent Boundary Layers", MSME thesis, (Aug. 1981).

2. Bogucz, E.A., "Separation of Turbulent Boundary Layers", Ph.D. thesis, (Aug. 1982).

3. Johansen, J.J., "Visualization of the Effect of Longitudinal Surface Modifications on Streak Formation and Bursting in Turbulent Boundary Layers", MSME thesis (Aug. 1982).

4. Acarlar, M.S., "Creation of Synthesized Turbulent Structure Using Surface Modifications", Ph.D. thesis (Dec. 1983).

5. S. Ersoy, "The Motion and Effects of Multiple Vortex Boundary Layers", Ph.D. Thesis, (Dec. 1982).

6. Cerra, A.W. (M.S.), "Vortex Loop-Boundary Layer Interaction," (August 1981).

7. Wei, T. (M.S.), "Determination of Turbulence Flow-Field Characteristics Using a Digitized Flow Visualization Technique," (June 1982).

REPORTS AND PUBLICATIONS - (see list on p. 17)

OTHER SUPPORTING GRANTS & CONTRACTS - None at present.

PERSONNEL

Co-Principal Investigators

D.E. Abbott, Professor and Chairman of Mechanical Engineering
C.R. Smith, Associate Professor of Mechanical Engineering
J.D.A. Walker, Associate Professor of Mechanical Engineering

Student Research Assistants

		(Comp. date)
S. Ersoy	Ph.D. Candidate	(Dec. 1982)
M.S. Acarlar	Ph.D. Candidate	(Dec. 1983)
E.A. Bogucz	Ph.D. Candidate	(Aug. 1982)
A.W. Cerra	MSME Candidate	(Aug. 1981)
T. Wei	MSME Candidate	(June 1982)
L.J. Yuhas	MSME Candidate	(Aug. 1981)
J.J. Johansen	MSME Candidate	(Aug. 1982)

HONORS, AWARDS, & DEGREES

None since last annual report dated 29 June 1980.

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